TECHNICAL REPORT NO. 11482

LABORATORY CONTROL OF DYNAMIC VEHICLE TESTING

December 1971

Approved for public release; Distribution Unlimited

by James W. Grant
Test & Evaluation Sub-Function
Frame, Suspension & Track Functions

TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

LABORATORY CONTROL OF DYNAMIC VEHICLE TESTING

December, 1971

BY

James W. Grant
Test & Evaluation Sub-Function
Frame, Suspension & Track Functions

U. S. Army Tank-Automotive Command
Warren, Michigan 48090

TABLE OF CONTENTS

ABSTRACT

In order to study vehicle suspension and frame dynamics under controlled and reproducible laboratory conditions, TACOM's road simulator or "shaker test" was developed. A road simulator is a laboratory test device which imparts dynamic forces simulating road inputs, on a complete vehicle. It is the purpose of this study to develop vertical position control signals for the road simulator so that good correlation between laboratory test and field results is obtained.

As a result of this study, the design engineer has a more exact vehicle model than he has had and the test engineer has a laboratory simulation which has been verified for vertical dynamic inputs. The combined effect of these two engineering tools will serve to produce a better prototype vehicle which, in turn, will eliminate many of the initial field test failures which plague new vehicles.

LABORATORY CONTROL OF DYNAMIC VEHICLE TESTING

INTRODUCTION

The road simulator concept of laboratory vehicle testing came into existence to facilitate studies of frame and suspension dynamics. Prior to the road simulator, frame and suspension components were divorced from the vehicle for laboratory evaluation. In most cases, the control or excitation signal for the test was some well defined mathematical function whose correspondence validity to actual field excitation is questionable. Testing then progressed to a point where recorded field signals and shaped random noise were used to control component tests.

Since there is interaction between the component being tested and the vehicle to which it is mounted, it became apparent that a road simulator which would test the total vehicle system in the laboratory would yield useful results. The early road simulators provided vertical inputs of low amplitude to each wheel of a passenger car. The inputs were accomplished using four electro-hydraulic linear actuators with pedestals on which the tires rested.

Laboratory testing of off-road vehicles offered a new challenge. Due to the large wheel deflections, the vehicle had to be restrained from falling off the road simulator. In order to facilitate restraining the vehicle and also to allow the addition of longitudinal excitation forces, the wheels were removed and the spindles attached to the actuator through a multiple degree of freedom assembly. The restraints were attached from vehicle to ground so that their effect on the dynamic motion of the sprung mass was minimal.

The present state of the art includes vehicles in the 5-ton payload class with up to six vertical and four horizontal linear actuators. Currently being constructed at the U.S. Army Tank-Automotive Command (TACOM) is a road simulator for 1/4-ton class vehicles which has four vertical actuators with position control, four horizontal actuators with load control and four rotary hydraulic pumps to be used as absorption dynamometers with torque control. This simulator, fully operational, will test the total vehicle system under controlled laboratory conditions.

The analog position of force signals which control the electro-hydraulic actuators must produce motions or forces in the vehicle which can be correlated with those which were recorded during field tests. This paper will present in detail three different techniques by which valid position control signals may be obtained from recorded field data or from surveyed terrain elevations.

CONTROL SIGNAL GENERATION TECHNIQUES

The analog signal which controls the electro-hydraulic actuators of the road simulator may be proportional to either position or force. The vertical road input actuators are position controlled and the fore and aft horizontal road input actuators are load controlled. The most readily obtained field data which can be transformed into vertical wheel spindle displacements are vertical accelerations of the wheel spindles. Terrain profile data can also be transformed into vertical wheel spindle displacement if accurate vehicle and tire models are on hand.

The field recorded fore and aft loads require no transformation if the actuators are load controlled. Force is proportional to acceleration, so the following analyses are applicable.

Double Integration

The acceleration signal which is to be double integrated is the vertical acceleration of the wheel spindle. The vertical accelerations of each wheel are recorded simultaneously so that the control signals generated from these accelerations will have the proper phase relationship. The acceleration signals thus recorded are a function of the suspension geometry, the suspension parameters, the tire characteristics and the terrain profile. Changes in any of the above vehicle characteristics would require that a new test course traverse be made. For the following analysis, assume that an accurate recorded acceleration signal is available.

The integral of well defined mathematical functions can be found in any calculus text. Mathematically, the integral of a continuous random variable such as vertical wheel acceleration is also well defined. In fact, the double integral of acceleration which results in displacement is also well defined. The physical implementation of double integration, however, is not well defined.

It is a well known fact that a stable perfect double integrator which has the transfer function $G_1(S) = 1/S^2$ is not physically realizable. The task, then, is to develop a stable transfer function, the frequency response of which approaches a double integrator in the desired frequency band of .5 to 50 Hz. This band is within the response limits of most road simulators and also includes the frequencies of interest for suspension dynamics studies. The transfer function chosen to double integrate the recorded acceleration signal to produce the position control signal for the road simulator is $G_2(S) = \frac{KS^2}{(S+4)^4}$

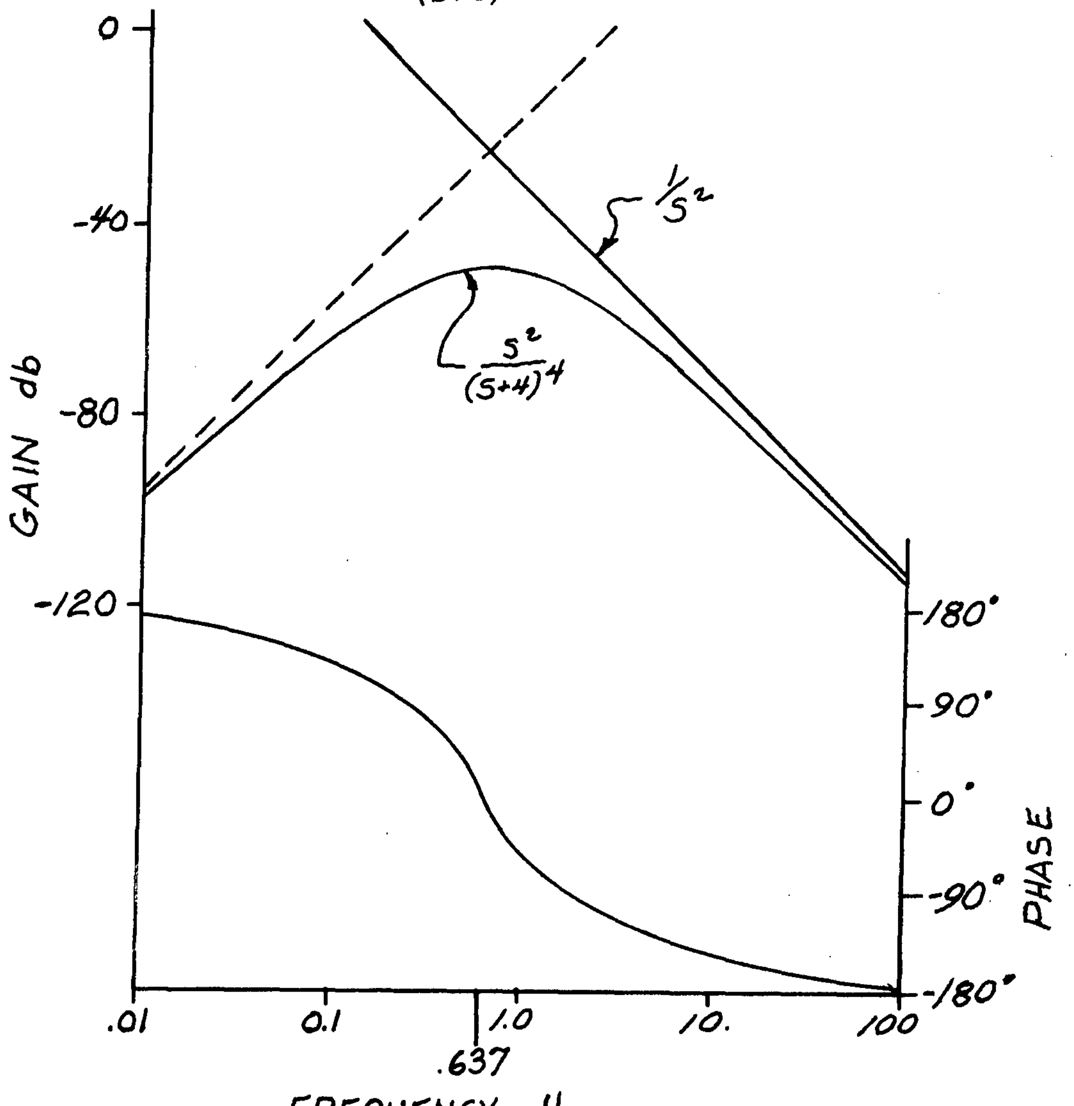

FIGURE 1. BODE PLOT

As can be seen in Figure 1, the frequency response curve for $G_2(S)$ when $K = 1$ asymptotically approaches perfect double integration beyond .636 Hz. The important characteristic of $G_2(S)$ is that the low frequency components of the input signal are suppressed. These low frequency components, especially zero frequency of D.C. offset, are the prime contributors to unstable double integration. This fact is quite clear in Figure 1. As frequency approaches zero, $G_1(S)$ approaches infinity and $G_2(S)$ approaches zero. The low frequency accuracy of $G_2(S)$ can be theoretically improved by shifting the intersection if its asymptotes to the left. This can be accomplished by decreasing the constant 4 in the denominator to 3, for example. However, as this constant approaches zero, $G_2(S)$ approaches $G_1(S)$. Another way to increase low frequency accuracy is to increase K. Increasing K, however, raises the whole response curve and the higher frequency accuracy decreases. Stability is also reduced as K is increased. Either method requires trial and error to determine which K or which denominator gives acceptable response in the desired frequency range.

Figure 2 shoes the result of playing a field-recorded acceleration signal into $G_2(S)$ with $K = 1$. The acceleration signal was recorded at the front wheel spindle of an M656 5-ton 8x8 cargo truck as it traversed the Aberdeen Proving Ground Belgian Block Course at an average speed of 15 miles per hour. The displacement signal peak to peak magnitude of .2 feet (Figure 2) was observed during the recording of the acceleration tape.

The accuracy of the approximate double integration depends, of course, upon the transfer function used to perform this operation. The correlation between the field recorded vertical acceleration of the wheel and the laboratory recorded vertical acceleration of the wheel can be computed to numerically determine the accuracy of the double integration.

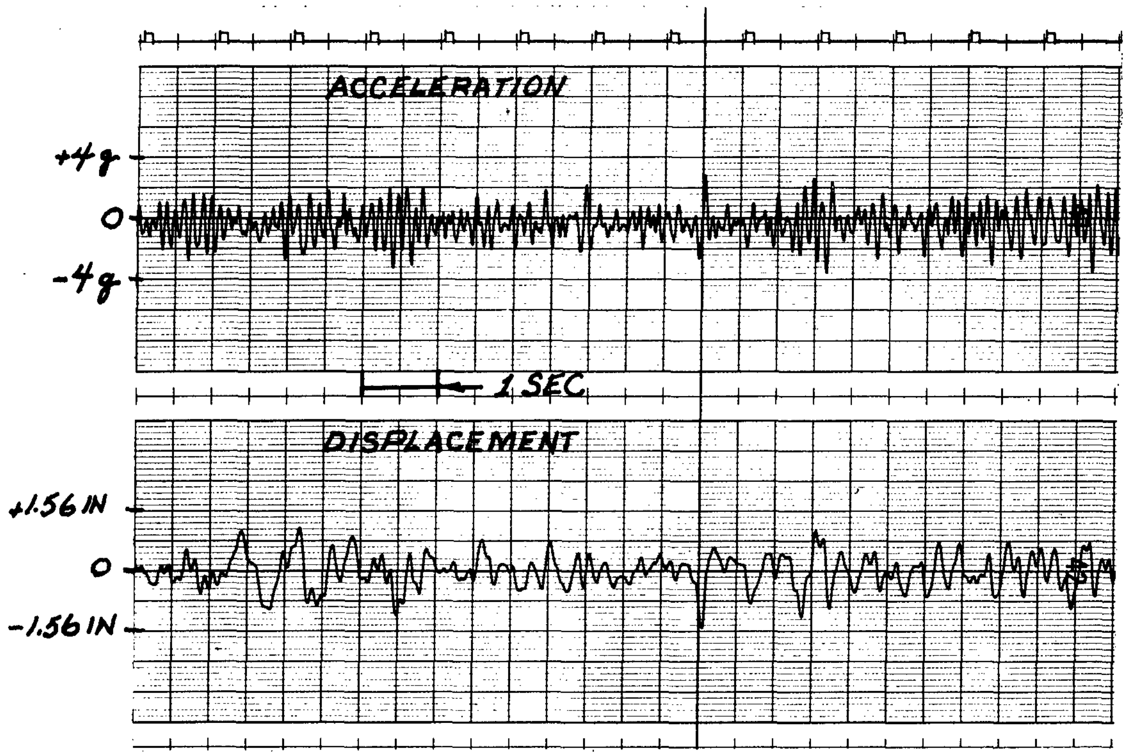

FIGURE 2. ACCELERATION & DISPLACEMENT-TIME CURVES

Filtered Noise

The idea of playing random noise, which has a flat power spectrum, through a shaping filter to control a laboratory road simulator has been suggested previously (references 1 and 2).

In order to apply this control technique, the vertical wheel spindle acceleration must be recorded on magnetic tape during field runs. From this data, a shaping filter for random noise is desired such that the filter output is a displacement signal statistically equivalent to the recorded acceleration signal.

Let the filter to be defined be a linear time invariant function so that conventional methods of analysis may be used. The total system is:

$$y(t) = h(t) \times n(t) \tag{1}$$

Where--

$n(t)$ is the random noise input
$h(t)$ is the filter
$y(t)$ is the output displacement

Using the convolution integral and fourier transform, as described in reference 3, page 182, the following relationship is obtained from equation (1):

$$S_{dd}(f) = |H(j2\pi f)|^2 \quad S_{nn}(f) \tag{2}$$

Where--

$S_{dd}(f)$ is the power spectral density (PSD) of the desired displacement control signal

$S_{nn}(f)$ is the PSD of random noise. This is a constant and will be defined to be unity

$H(j2\pi f)$ is the frequency response function for the shaping filter

The relationship between displacement and acceleration PSD's is defined to be:

$$S_{dd}(f) = \frac{1}{(2\pi f)^4} \cdot S_{aa}(f) \tag{3}$$

Substituting $S_{dd}(f)$ in equation (3) gives:

$$S_{aa}(f) = (2\pi f)^4 \; |H(j2\pi f)|^2 \quad S_{nn}(f) \tag{4}$$

Since $S_{nn}(f) = 1$ by previous definition:

$$H(j2\pi f) = \frac{1}{(2\pi f)^2} \cdot \sqrt{S_{aa}(f)} \tag{5}$$

Equation (5) will now be used to obtain from field data the frequency response for the desired filter.

Figure 3 is a PSD curve of the vertical front wheel acceleration of an M656 5-ton 8x8 cargo truck. The acceleration signal was recorded during field tests as Aberdeen Proving Ground at an average vehicle speed of 14.2 miles per hour. The test courses were the Belgian Block Course, Three-Inch Spaced Bump Course, Two-to-Four-Inch Radial Washboard Course, Imbedded Rock Course and Two-Inch Washboard Course. Substituting the values for $S_{aa}(f)$ from Figure 3 into Equation (5) results in the desired frequency response curve shown in Figure 4. The desired curve was approximated using an ESIAC algebraic computer by the following transfer function where $j2\pi f$ is replaced by the Laplace Operator S:

$$H(S) = \frac{15.123\ (S^2 + 86.4\ S + 202S)}{(S^2 + 10.5S + 122S)\ (S^2 + 5S + 25)} \tag{6}$$

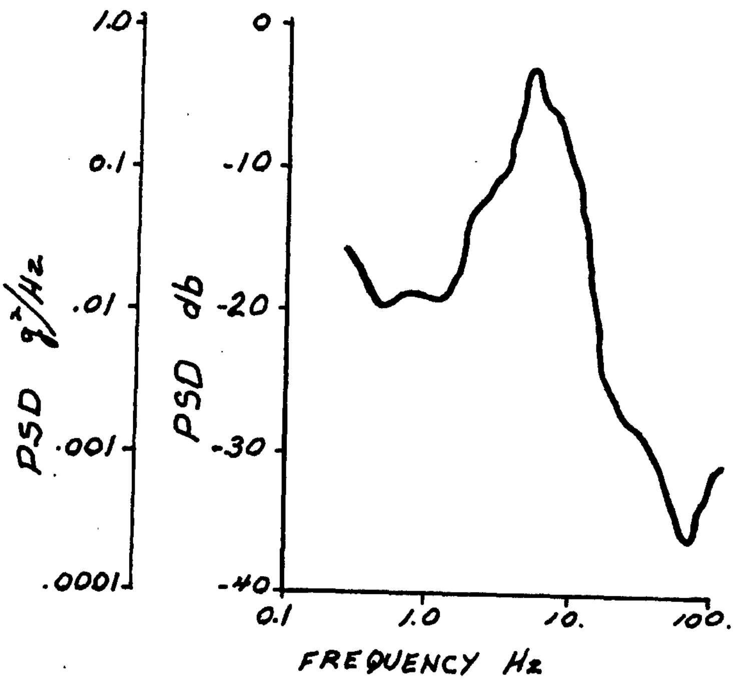

FIGURE 3. PSD OF FIELD RECORDED VERTICAL WHEEL ACCELERATION

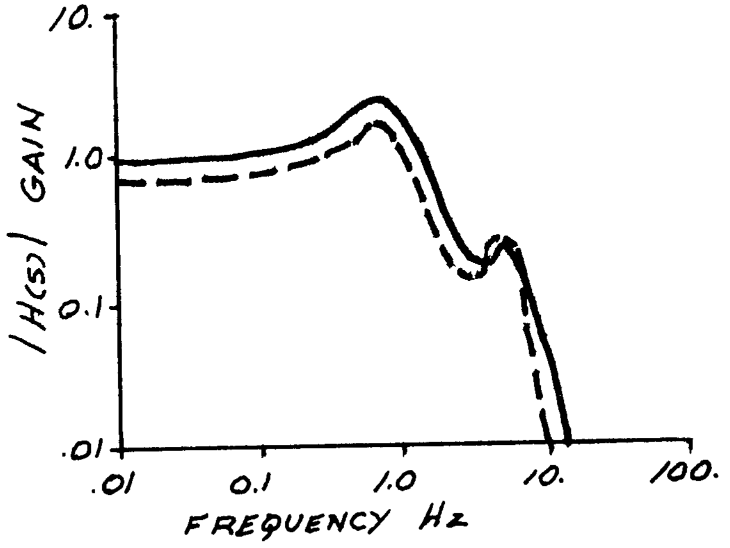

FIGURE 4. FREQUENCY RESPONSE CURVES FOR DESIRED AND ACTUAL FILTERS

The actual frequency response curve for Equation (6) is the dashed curve in Figure 4. Figure 5 is the output of the filter with a random noise input.

Since PSD is an approximate measurement and the actual filter response function is an approximation of the desired filter response function, the accuracy of this technique depends upon the accuracy of the approximations. This technique is validated using statistical measurement techniques such as histograms, cross correlation and probability density functions.

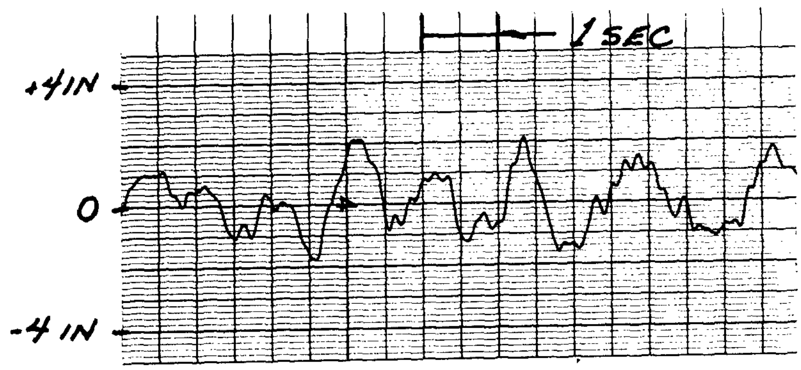

FIGURE 5. POSITION CONTROL SIGNAL

Terrain Profile

The two previous methods of control signal generation required that vehicle dependent acceleration signal at the wheel spindle be recorded during test course traverse. In other words, new instrumented test runs must be made for each different vehicle configuration. Consider now the possibility of using surveyed terrain profiles to control the road simulator system where the excitation is through the wheel spindle as previously stated.

Surveyed terrain elevation data are readily available, in reference 4 for example. The major problem to be solved then is the transfer function from terrain to the wheel spindle. This transfer function represents not only the tire assembly dynamics but is also a function of the suspension dynamics and the sprung mass. It is concluded then that a mathematical model of the total vehicle system is required. This model would be programmed on an analog or hybrid computer and run in parallel with the road simulator to provide the wheel spindle position control signal. The block diagram of this system is shown in Figure 6.

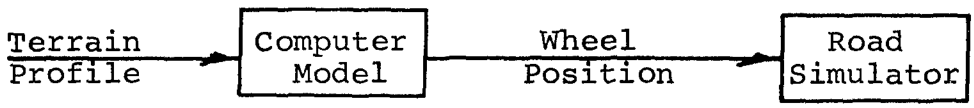

FIGURE 6

System Block Diagram

The system in Figure 6 assumes an accurate model of both the tire and the vehicle. The tire is a complex non-linear system which is discussed thoroughly in reference 5. A tire model can be made so complex that it is unwieldy or it can be simplified to a second order mass-spring-damper system. The latter case with a realistic non-linear spring and point follower, Figure 7, may give satisfactory results for the vertical control of a road simulator.

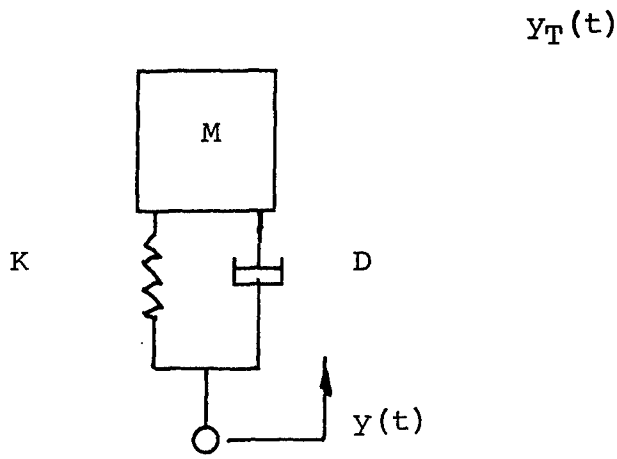

FIGURE 7

Simple Tire Model

Where--

M is the unsprung mass
K is the spring rate
D is the damping coefficient
y(t) is the terrain profile
$y_T(t)$ is the wheel displacement

NOTE that the velocity profile, $\dot{y}(t)$, of the terrain is also required. The digitized terrain profile is digitally differentiated to obtain $\dot{y}(t)$.

Obtaining an accurate mathematical model of the vehicle dynamics is facilitated by the availability of the road simulator. The differential equations of motion for the vehicle are obtained using any of the conventional techniques such as Lagrangian or Newtonian mechanics. The equations are then programmed on an analog or hybrid computer. The computer model and the road simulator are excited at the wheel spindles with identical signals and the responses are compared. The response is a combination of sprung mass output signals, which could include, for example, pitch, bounce and roll displacements. The parameters of the computer model are adjusted either manually or automatically such that the error between comparison signals is minimized. Reference 6 presents a continuous parameter tracking technique which could be extended to attain the automatic parameter adjustment.

Once the accurate model is obtained, its parameters may be easily adjusted to maximize some index of performance such as driver comfort. The sensitivity of any performance parameter to changes in each of the physical vehicle parameters can be measured. This type of study tells the design engineer a range of acceptable values for each physical parameter. The physical parameters include spring rates, damping coefficients, center of gravity location, wheel base, etc.

The above described technique is an ambitious undertaking currently being implemented at TACOM. Extensive computer analysis is required, but the resulting vehicle model will give the design engineer a new tool with which to improve vehicle performance.

SUMMARY

Three methods for obtaining the road simulator control signal (the input at the wheel spindle of the test vehicle) have been presented.

The double integration of field recorded vertical wheel spindle acceleration and the filtered random noise both require field data acquired by a vehicle similar to the test vehicle. These two methods are well suited to long term durability studies.

The third method requires and facilitates the development of an accurate mathematical model of the vehicle. The selected terrain profile is played into the computerized vehicle model and the wheel displacement signals from the model are then used to control the road simulator.

The first two techniques have been used at TACOM to control simulators. The third technique is currently being implemented; we expect to be using it by December 1971

REFERENCES

1. Van Deusen, B.D., et al, "Experimental Verification of Surface Vehicle Dynamics", NASA CR-1399, National Aeronautics and Space Administration, Washington, D.C., September, 1969.

2. Van Deusen, B.D., "A Statistical Technique for the Dynamic Analysis of Vehicles Traversing Rough Yielding and Non-Yielding Surfaces", NASA CR-659, National Aeronautics and Space Administration, Washington, D.C., March, 1967.

3. Davenport, W.B., Jr., and Root, W.L., "An Introduction to the Theory of Random Signals and Noise", McGraw-Hill Book Co., Inc., New York, N.Y., 1958.

4. Heal, S., and Cicillini, C., "Micro Terrain Profiles", RRC-9, U.S. Army Tank-Automotive Center, Warren, Michigan, 14 August 1964.

5. Schuring, D., and Belsdorf, M.R., "Analysis and Simulation of Dynamical Vehicle-Terrain Interaction", Cornell Aeronautical Laboratory, Inc., Cornell University, Buffalo, N.Y., May, 1969.

6. Jackson, G.A., and Grant, J.W., "Linear Suspension System Parameter Identification", SAE 710227, Automotive Engineering Congress, Detroit, Michigan, January, 1971.

DISTRIBUTION LIST

ADDRESSEE	NO. OF COPIES
Commanding General U.S. Army Tank-Automotive Command Warren, Michigan 48090 ATTN:	
Research, Development & Engineering Directorate, AMSTA-R	1
Chief Scientist, AMSTA-CL	1
Chief Engineer, AMSTA-CR	1
Systems Development Division, AMSTA-RE	2
Transport Vehicle Branch, AMSTA-RGB	10
Foreign Technology-International Affairs Office, AMSTA-RI	1
Technical Data Division, AMSTA-RS	1
Mobility Systems Laboratory, AMSTA-RU	1
Frame, Suspension & Track Programs, AMSTA-RUT	15
Propulsion Systems Laboratory, AMSTA-RG	1
Diognostic Equipment Branch, AMSTA-RGD	1
Vehicular Components & Materials Laboratory, AMSTA-RK	1
Laboratory Support Section, AMSTA-RKAS	1
Materials Branch, AMSTA-RKM	1
Vehicle Branch, AMSTA-QED	2
M60 Tank, AMCPM-M60	1
Mechanized Infantry Combat Vehicle, AMCPM-MCV	1
Armored Reconnaissance Scout Vehicle, AMCPM-RSV	1
M561/XM705 Trucks, AMCPM-GG	1
Main Battle Tank, Engineering Agency, AMCPM-MBT-EA	1
US Marine Corps Liaison Office, USMC-LNO	1
US Army Electronics Command Liaison Office, AMSEL-RD-LN	1
US Army Weapons Command Liaison Office, AMSWE-LCV	1
US Army Combat Developments Command Liaison Office, CDCLN-A	2
Canadian Forces Liaison Office, CDLS-D	1
US Marine Corps Liaison Office, MCSA-LNO	1
Commanding General U.S. Army Materiel Command ATTN: AMCRD-GV Washington, D.C. 20315	1

DISTRIBUTION LIST
(cont'd)

ADDRESSEE	NO. OF COPIES
Commanding General U.S. Army Weapons Command ATTN: AMSWE-RDR Rock Island, Illinois 61202	1
Commanding General U.S. Army Test & Evaluation Command ATTN: AMSTE-TA AMSTE-BB Aberdeen Proving Ground, Maryland 21005	1
Commanding General Engineering Research & Development Laboratory Fort Belvoir, Virginia 22060	1
Commanding General U.S. Army Combat Developments Command Fort Belvoir, Virginia 22060	1
Commanding General U.S. Army Combat Developments Command Combat Arms Group ATTN: Materiel Division Fort Leavenworth, Kansas 66027	1
Commanding General U.S. Army Combat Developments Command Combat Service Support Group ATTN: Materiel Division Fort Lee, Virginia 23801	1
Commanding Officer Watervliet Arsenal Watervliet, New York 12189	1
Commanding Officer Frankford Arsenal ATTN: SMUFA-L7000, Technical Library Bridge & Tacony Streets Philadelphia, Pennsylvania 19137	1

DISTRIBUTION LIST
(cont'd)

ADDRESSEE	NO. OF COPIES
Commanding Officer Rock Island Arsenal Rock Island, Illinois 61202	1
Commanding Officer Picatinny Arsenal Dover, New Jersey 07801	1
Commanding Officer U.S. Army Materials & Mechanics Research Center ATTN: Mr. William P. Hatch Mr. Arthur F. Jones Watertown, Massachusetts 02172	 1 1
Commanding Officer Materiel Test Directorate ATTN: STEAP-MT, Mr. W. C. Pless Technical Library Aberdeen Proving Ground, Maryland 21005	 1 2
Commanding Officer Yuma Proving Ground Yuma, Arizona 85364	1
Commanding Officer U.S. Army Natick Laboratories ATTN: Technical Library Natick, Massachusetts 01762	1
Commanding Officer Harry Diamond Laboratories ATTN: AMXDO, Library Connecticut Avenue & Van Ness Street, N.W. Washington, D.C. 20438	1
Director Naval Research Laboratory ATTN: Technical Information Center Anacostia Station Washington, D.C. 20390	1

<u>DISTRIBUTION LIST</u>
(cont'd)

ADDRESSEE	NO. OF COPIES
Commandant U.S. Marine Corps ATTN: Code A0411 Washington, D.C. 20380	1
Commander Air Force Materials Laboratory Wright Patterson Air Force Base, Ohio 45433	1
Headquarters Defense Documentation Center for Scientific & Technical Information ATTN: Document Service Computer Center Cameron Station Alexandria, Virginia 22314	20
Defense Materials Information Center Battele Memorial Institute 505 King Avenue Columbus, Ohio 43201	1
Director U.S. Army Production Equipment Agency Rock Island Arsenal Rock Island, Illinois 61202	1

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Test & Evaluation Sub-Function Frame, Suspension & Track Functions Surface Mobility Division	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Laboratory Control of Dynamic Vehicle Testing

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

James W. Grant

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December, 1971	20	6

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 11482 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; Distribution Unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

In order to study vehicle suspension and frame dynamics under controlled and reproducible laboratory conditions, TACOM's road simulator or "shaker test" was developed. A road simulator is a laboratory test device which imparts dynamic forces simulating road inputs, on a complete vehicle. It is the purpose of this study to develop vertical position control signals for the road simulator so that good correlation between laboratory test and field results is obtained.

As a result of this study, the design engineer has a more exact vehicle model than he has had and the test engineer has a laboratory simulation which has been verified for vertical dynamic inputs. The combined effect of these two engineering tools will serve to produce a better prototype vehicle which, in turn, will eliminate many of the initial field test failures which plague new vehicles.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
ROAD SIMULATORS						
DOUBLE INTEGRATION						
TRANSFER FUNCTION						
SHAPING FILTER						
TERRAIN SYNTHESIS						
MATHEMATICAL MODELING						
SERVO CONTROL						
LABORATORY TESTING						
VEHICLE DYNAMICS						